Available online at www.sciencedirect.com
SCIENCE DIRECT®
Catena 56 (2004) 199–212
CATENA
www.elsevier.com/locate/catena

Runoff and erosion in volcanic soils of Azores: simulation with OPUS

J.C. Fontes[a], L.S. Pereira[b,*], R.E. Smith[c]

[a] University of Azores, 9700 Angra do Heroísmo, Portugal
[b] Agricultural Engineering Research Center, Institute of Agronomy, Technical University of Lisbon, Portugal
[c] USDA-ARS and Colorado State University o, 301 South Howes, Ft. Collins, CO 80522, USA

Abstract

The islands of Azores are of very recent volcanic origin and their soils have special physical and chemical characteristics because of the specific circumstances of their formation from the volcanic materials, their young age and the presence of allophane. To assess and understand the hydrologic behavior of these soils under agricultural practices, the deterministic model OPUS was tested and calibrated using field data collected from 1996 to 1998 in two small basins of Terceira Island. The model uses a solution of the Richards' equation to simulate water movement in the soil profile, which requires modified Brooks and Corey equations to describe the soil hydraulic characteristics. For runoff, the model uses either a mechanistic simulation with the Parlange and Smith infiltration equation or the Soil Conservation Service (SCS) Curve Number (CN) approach. In the first, a mechanistic detachment and transport model is used to simulate erosion, and for the second the modified universal soil loss equation (MUSLE) is utilized. Results of the model simulations for runoff and erosion match the observed data well. Runoff significantly increased from 1% to 17% of rainfall from pasture to bare soil or partially covered soil during establishment of a new pasture. Sediment yields sharply increased from <5 kg ha^{-1} year^{-1} under pasture to nearly 15 ton ha^{-1} during the 8-month period when the soil was unprotected.

Keywords: Azores; Andosols; Land use; Rainfall–runoff; Erosion; Deterministic modeling

1. Introduction

Assessment of the effects of land use on hydrologic processes is important to support decisions on soil management. The use of simulation models is of particular interest

* Corresponding author. Fax: +351-21-362-15-75, +351-21-363-50-31.
E-mail addresses: jfontes@notes.angra.uac.pt (J.C. Fontes), lspereira@isa.utl.pt (L.S. Pereira), sroger@engr.colostate.edu (R.E. Smith).

0341-8162/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.catena.2003.10.011

because several land use and management scenarios can be evaluated and the information produced can be used to select practices that lead to resource conservation and sustainable use of the soil. Several models have been developed for these purposes using different conceptual, time and area scales (Musy et al., 1999). However, models require previous calibration and validation, especially when used in conditions different from those in which they have been previously applied and tested.

This is true for the soils of the Azores Islands, which are of very recent volcanic origin and have unusual hydraulic characteristics related to the presence of allophane (Fontes et al., 2004). Agricultural systems in the Azores are based on pasture lands for direct grazing in a long rotation of several years with silage maize. The soil is periodically disturbed to plant maize and later to replant the pasture. Other agricultural crops are also cultivated, but in lower lands on slopes more gentle than the pasture lands.

OPUS (Smith, 1992, 1995) is an agricultural hydrologic simulation model previously used for runoff and erosion predictions in different environments (e.g. Diekkrueger et al., 1991) but not for volcanic soils such as those in Azores. Because these soils have specific hydraulic properties related to the presence of allophane (Fontes et al., 2004), we aimed to understand better their hydrologic behavior under different land uses, and to calibrate and test the model. The results are also analyzed for further use of the OPUS model in a wider study aimed at a better description of land use environmental impacts on the volcanic soils of Azores.

2. Model description

OPUS (Smith, 1992, 1995) was developed from the model CREAMS (Knisel, 1980) to simulate single or multiple rainfall–runoff events and processes of water flux and nutrient transportation. It deals with the space over and within small catchments, from above the plant to below the root zone in the soil. All soil hydraulic processes are computed one-dimensionally in the vertical direction, as one soil column for the whole slope. At the soil surface, processes such as surface runoff and erosion are calculated one-dimensionally in the direction of the slope. Consequently, the soil surface has to be divided into several segments, and runoff and erosion rates computed for each segment.

The water flux in the soil is described by the well-known Richards Equation, which is solved by the numerical method of finite differences. The soil depth is divided into finite layers in which the soil water suction head h [mm] and the water content θ [$mm^3\ mm^{-3}$] are computed. This procedure requires knowledge of the soil water retention curve $\theta(h)$ and the hydraulic conductivity curve $K(h)$.

The $\theta(h)$ relationship is described by a modified Brooks and Corey (1964) model:

$$\Theta = \left[1 + \left(\frac{h}{h_{\mathrm{b}}}\right)^{c}\right]^{-\lambda/c} \tag{1}$$

where Θ is the normalized volumetric water content defined as

$$\Theta = \frac{\theta - \theta_{\mathrm{r}}}{\theta_{\mathrm{s}} - \theta_{\mathrm{r}}} \tag{2}$$

in which θ_r is the residual water content [$mm^3\ mm^{-3}$] and θ_s is the saturated water content [$mm^3\ mm^{-3}$], h_b is the air entry potential head [mm], λ is a pore size distribution parameter, and c is a curvature coefficient affecting the shape of the curve near h_b [−]. This relation (2) reduces towards the original model of Brooks and Corey as c becomes large. The hydraulic conductivity K [$mm\ min^{-1}$] is described by

$$K = K_s \Theta^{\varepsilon} \tag{3}$$

in which K_s is the effective saturated hydraulic conductivity [$mm\ min^{-1}$] and the exponent ε is approximated by:

$$\varepsilon = \frac{2 + 3\lambda}{\lambda} \tag{4}$$

The lower boundary condition for the model is the depth of the water table or of the tile drains if these exist. For the upper boundary, the infiltration and evapotranspiration rates are necessary. The infiltration can be calculated in two different ways, depending on whether breakpoint rainfall data or only daily rainfall depths are available. If breakpoint data are available, infiltration is calculated using the infiltration equation developed by Smith and Parlange (1978):

$$f = K_s \frac{\exp(I/G)}{\exp(I/G) - 1} \tag{5}$$

where f is the rate of infiltration [$mm\ min^{-1}$], I is the depth of infiltration from start of rainfall [mm], $G = G(\theta_i)$, is a capillary scale parameter [mm] and θ_i is the initial soil water content [$mm^3\ mm^{-3}$]. The capillary scale parameter, $G(\theta_i)$, is a coefficient depending on initial conditions and is related to the integral properties of the soil capillary characteristics (Smith, 1992) by:

$$G(\theta_i) = \frac{\theta_s - \theta_i}{K_s} \int_{-\infty}^{0} K(h)\mathrm{d}h \tag{6}$$

The water flux model provides the initial conditions needed for the infiltration equation. This equation is extended when considering a transient surface crust.

When the infiltration simulation model begins to produce rainfall excess, water begins to move over the surface. The Saint-Venant (1871) equations are used to describe the dynamics of catchment runoff, which are solved by the kinetic method for all but very flat slopes or, for the latter, by a diffusive wave equation. Sediment production is computed using the Foster (1982) equation, if breakpoint rainfall data are available. It is a function of the effective rainfall intensity, inter-rill surface-slope angle, soil coverage by plants and mulch, flow depth over the soil surface, and a surface-soil residue factor that expresses the protective effect of crop residues. Sediment transportation is computed as a function of time and distance using the Bennett (1974) equation.

When daily rainfall data are provided, the model uses the Soil Conservation Service (SCS) Curve Number (CN) runoff-estimation method (Soil Conservation Service, 1972) with some modifications. To compute runoff amount (Q) from rainfall depth (P) as a function of the initial abstraction (I_a) and the soil water storage (S), S is estimated from the actual water content of the upper soil layers and the CN number characterizing the soil and its cover. P, Q, I_a and S are expressed in millimetres. To increase accuracy, CN is calibrated from observed data for wet, average and dry antecedent soil moisture conditions. The saturated hydraulic conductivity is then estimated from CN using the Morel-Seytoux and Verdin (1983) equations. The water retention in the soil is computed using the equation proposed by Williams et al. (1990) as a function of the soil water content at field capacity and the wilting point for the same antecedent moisture conditions as CN.

If daily rainfall data are used, the sediment production is estimated with the modified universal soil loss equation (MUSLE) equation (Williams et al., 1984; Sharpley and Williams, 1990). The erosivity factor is computed from both the rainfall intensity and the runoff, the soil erodibility is estimated from soil data, the topographic factor is computed from the basin surface topographic characteristics, and the soil cover and conservation practices factors are determined from the crop canopy and management practices.

Evapotranspiration is computed with the Ritchie equation (Ritchie, 1972) modified to consider the soil water and plant conditions, including factors influencing soil shading. To generate data on plant and soil water conditions, a plant growth model is included in OPUS, which relates the crop growth rate to solar radiation, nutrients, temperature and water availability.

3. Materials and methods

Two small experimental basins have been installed on Terceira in an area where the main land use is pasture. The basin Granja (GRA), whose area is 3500 m^2 and average slope 8.9%, is located at 38° 41′ 55″ N, 27° 10′ 14″ W, with an elevation of 380 m at the outlet. The basin Ribeirinha (RIB) has an area of 1830 m^2 and an average slope of 16.4%, and is located at 38° 40′ 21″ N, 27° 10′ 41″ W, at 400 m elevation. RIB was under grazing pasture, mainly *Lolium perenne* and *Trifolium repens*, for all the observation period. GRA had a similar pasture during the initial period of observation, January 96 to April 97, but was planted with maize (*Zea mays* var. licinio) by April 97, which was harvested for silage by the end of September. A new pasture was installed by October 97 and attained full cover by May 98.

Because the conceptual approach in OPUS emphasizes soil water simulation, field observations in soil monoliths and laboratory measurements were used to determine the hydraulic properties of the soils (Fontes et al., 2004). Soil water content was monitored in the field by neutron probe with variable frequency at each 20 cm to the entire depth of each profile, and by gravimetric determination for the surface layer. The neutron probe was calibrated for the full range of observations.

Infiltration data were obtained experimentally using a double ring infiltrometer modified to maintain a constant charge in the inner and outer areas. Sensors of the water level in the inner and the outer rings were used to control water supply. A water level sensor was also installed in the reservoir feeding the inner ring, and all levels were recorded by a data acquisition system with a time step of 1 min. Measurements for successively lower soil layers were made after removing overlying soil layers, and were taken at several locations and repeated two or three times at each site.

Automatic weather stations were installed near the basin outlets equipped with sensors for air temperature, wet and dry bulb temperature, wind speed and direction, global solar radiation, precipitation and soil temperature. Data were recorded digitally with a time step of 2 min and aggregated to other time steps according to the model requirements. The runoff discharges were measured with a V-notch weir using a sensor connected to the same digital recorder. Runoff volumes were measured in sedimentation tanks, which were fed after fractionating the runoff flow. The tanks were also used for water and sediment sampling.

The model was parameterized using data on the basin topology, climate, soil and crops. Evapotranspiration (ET) estimated by the Ritchie equation was calibrated against Penman–Monteith computations based on the same data sets, using regression through the origin to compare results from both equations. The best regression and determination coefficients were found using successive computations with the Ritchie equation. The soil water retention and hydraulic conductivity curves were fitted after evaluating the quality of laboratory measurements as discussed by Fontes et al. (2004). The $\theta(h)$ and $K(h)$ parameters were then evaluated by regressions forced through the origin between measured and calculated $\theta(h)$ and $K(h)$ values, and the average errors of estimates (AEE) were calculated. The AEE represents the average value of the absolute difference between observations and estimates for every data set analyzed.

The infiltration curves were fitted by successive adjustments of the infiltration parameters using the two-step method (Cameira et al., 2000). First, the experimental data were fitted taking into consideration that ring infiltrometer measurements tend to overestimate the steady-state infiltration (Rawls et al., 1996). Then the estimated parameters were improved by running the OPUS model to simulate the soil water storage after setting the $\theta(h)$ and $K(h)$ parameters and calibrating the evapotranspiration equation. Therefore, the infiltration parameters were not evaluated in relation to the observed infiltration curves but through the accuracy of model simulation of the soil water storage. When daily rainfall data were used, the CN parameter was calibrated by combined analysis of the observed runoff hydrographs and the rainfall breakthrough curves for the same runoff events. Calibrated values for CN were therefore selected for wet, average and dry antecedent soil moisture conditions. The OPUS model was then run to simulate the soil water storage to test the accuracy of the CN parameters. Model parameters for rainfall erosivity, soil erodibility and the effects of crop practices used with MUSLE were calibrated using the observations on sediment production under grass and bare soil, which were compared with model simulations for the same periods.

4. Results and discussion

4.1. Soil water and evapotranspiration

To simulate the soil water storage, special attention was paid to the quality of input data for soil hydraulic properties. The parameters describing the $\theta(h)$ and $K(h)$ curves

Table 1
Parameters describing the $\theta(h)$ and $K(h)$ curves and the Smith and Parlange (1978) infiltration equation for the GRA and RIB soils

	Soil layers (cm)	Soil hydraulic parameters						
		θ_r	θ_s	h_b (mm)	λ	c	K_s (mm h^{-1})	$G(\theta_i)$
GRA	0–19	0.22	0.67	200	0.42	1.5	19.1	6.0
	20–40	0.22	0.62	170	0.46	1.5	37.5	14.0
	40–65	0.25	0.73	100	0.08	2.0	33.3	34.5
	65–85	0.42	0.78	150	0.10	2.0	5.4	14.9
	85–100	0.15	0.70	100	0.45	2.0	20.8	15.0
RIB	0–15	0.26	0.60	110	0.28	2	25.0	16.2
	15–40	0.23	0.70	120	0.25	1.5	12.5	68.0
	40–90	0.33	0.68	150	0.28	1.7	12.5	52.0

(Eqs. 1–4) and infiltration (Eqs. (5) and (6)) are given in Table 1. These parameters reflect the unusual characteristics of Andosols with allophane, which are distinctly different from soils for which the model has been used before. They have very low bulk density, large total porosity and very high water-holding capacity (Fontes et al., 2004). The water contents at saturation θ_s, field capacity and wilting point, and the residual water content θ_r, are much greater than those of non-allophane soils with similar textural characteristics. The high values for θ_s result from very high total porosity, which may be explained by the inter- and intra-particle porosities. The high porosity also explains the high saturated hydraulic conductivity K_s (Maeda et al., 1977; Parfitt, 1990).

The quality of fitting of both the soil water retention and the hydraulic conductivity curves is indicated by the parameters of the regression through the origin between measured and computed data using the modified Brooks and Corey model (Eqs. 1–4). For all but a few soil layers, the regression coefficient (b) is close to the 1:1 line (Table 2). Where b is significantly different from 1.0, it reflects the difficulties in estimating $\theta(h)$ and $K(h)$ discussed by Fontes et al. (2004), which again are due to the presence of allophane. Table 2 also presents the average errors of estimates (AEE) based on the differences

Table 2
Determination and regression coefficients for fitting the $\theta(h)$ and $K(h)$ curves and the respective average error of estimates (AEE) for all soil layers

Basins	Soil layers (cm)	Water retention curve $\theta(h)$			Hydraulic conductivity $K(h)$		
		R^2	b	AEE (cm^3 cm^{-3})	r^2	b	AEE (cm day^{-1})
GRA	0–19	0.99	1.01	0.008	0.92	1.02	1.42
	20–40	0.94	1.03	0.019	0.65	0.72	0.29
	40–65	1.00	0.94	0.006	0.88	0.59	2.15
	65–85	0.61	0.99	0.010	0.93	1.04	0.50
	85–100	0.94	0.96	0.031	0.94	0.83	1.01
RIB	0–15	0.94	0.95	0.026	0.76	1.17	3.53
	15–40	0.97	1.02	0.015	0.98	0.99	0.29
	40–90	0.94	1.00	0.008	0.75	1.03	1.13

between measured and estimated values of $\theta(h)$ and $K(h)$. These AEE indicate appropriate accuracy for using the modified Brooks and Corey functions as model inputs.

Typical infiltration curves observed for the soil surface layer (0–0.15 m) and fitted with the Smith and Parlange model (Eqs. (5) and (6)) are presented in Fig. 1 for both locations, RIB and GRA. They show a quite sharp decline in infiltration rate for the first 30 min of water application and a near steady infiltration for 1–10 h of observations. Fig. 1 also shows that fitting overcomes the common problem of overestimation of steady infiltration when ring infiltrometers are used. Infiltration is greater for RIB than for GRA. In addition to differences in soil characteristics, this may reflect the fact that the soil is not disturbed by cultivation at RIB.

The soil water simulation required the selection of parameters describing the crop cover to adequately represent the upper boundary of the soil. Thus, the empirical coefficient for wind and air humidity (c_w) in the Ritchie (1972) equation was calibrated by searching for the parameter value that produced estimates for grass evapotranspiration closer to the grass reference evapotranspiration computed with the Penman–Monteith equation (Allen et al., 1998). Observed daily weather data were used. Results presented in Fig. 2 for the 3 years of observations in RIB show that the estimates with the Ritchie equation have a larger variation than those by the Penman–Monteith equation. The differences are related to the concepts and approaches behind the two equations, the second being more consistent and better adapted to a large range of environments (Jensen et al., 1990).

The estimates by both ET equations were compared by the regression through the origin (Fig. 3). The regression coefficient after validation is $b = 1.02$, close to the 1:1 line, thus indicating that ET estimates with the model follow the trend of the Penman–Monteith computations. The determination coefficient is $r^2 = 0.73$, which expresses the large variation of estimates by the Ritchie equation, as discussed above.

The lower boundary for the soil water storage computations is free drainage. Fig. 4 shows that rainfall events are very frequent at both experimental locations. The total annual mean rainfall is near 2000 mm in both locations. Results for the simulated and observed soil water storage to 35-cm depth, the average depth explored by the grass roots, are represented in Fig. 5. These simulations used breakthrough rainfall data. The simulated

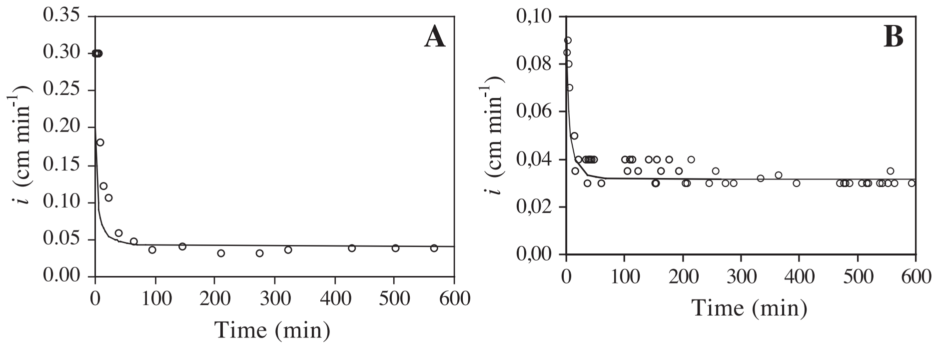

Fig. 1. Infiltration rate (i, cm min^{-1}) curves observed and fitted with the Smith and Parlange (1978) equation for the surface soil layer at (A) RIB and (B) GRA basins.

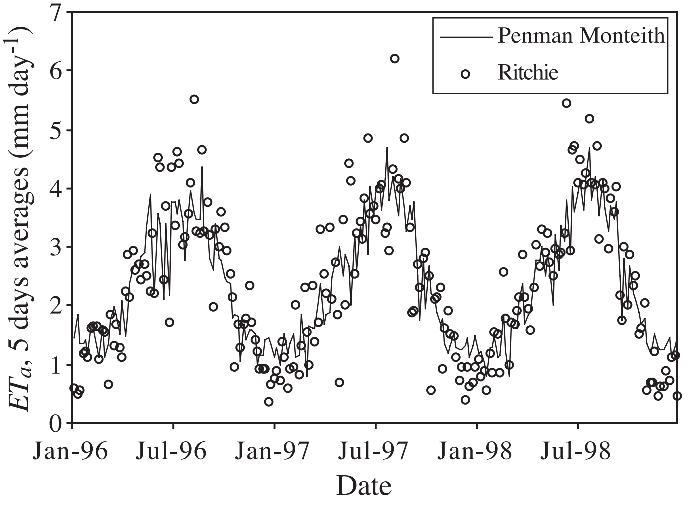

Fig. 2. Evapotranspiration simulated with the calibrated c_w coefficient in the Ritchie equation and computed with the Penman–Monteith equation using basin RIB weather data (dots refer to 5-day averages).

and observed soil water storage data were compared using a linear regression through the origin (Fig. 6). The regression coefficients (b) are 1.01 and 0.97 for RIB and GRA, respectively, and very close to the 1:1 line. The determination coefficients (r^2) are 0.84 for RIB and 0.82 for GRA. Simulation data tend to underestimate soil water storage in GRA when the soil is very dry, different from the simulations for RIB. Underestimation for GRA relates to difficulties in measuring and describing the soil hydraulic properties

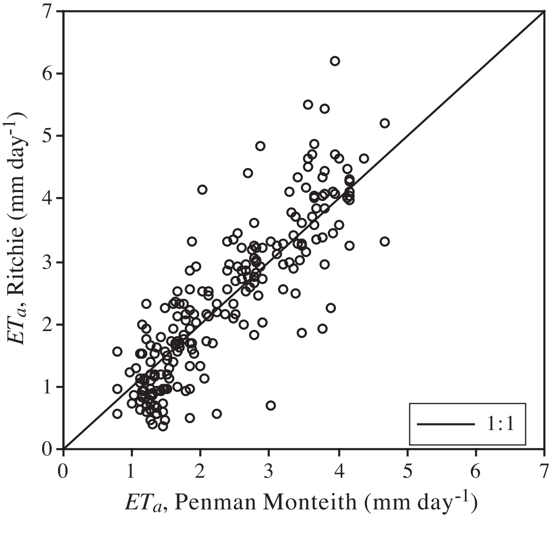

Fig. 3. Comparison of grass evapotranspiration estimates using the calibrated Ritchie equation (ET_a) and the grass reference evapotranspiration Penman–Monteith equation (ET_o).

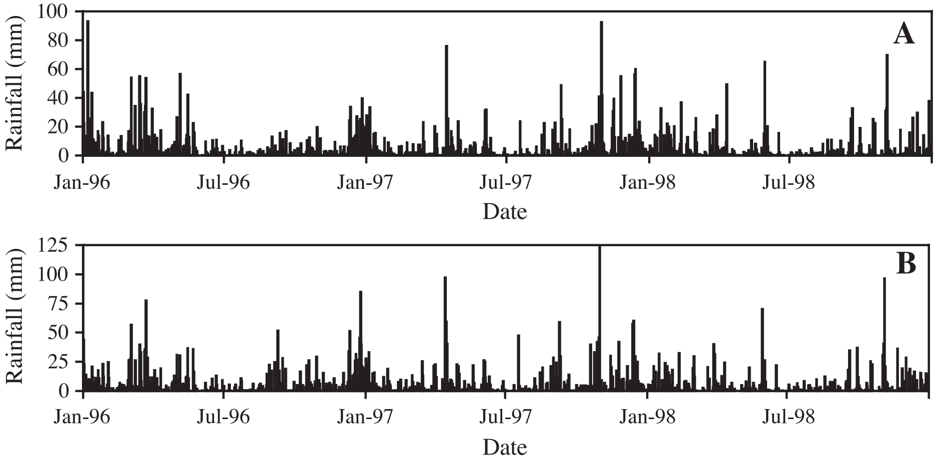

Fig. 4. Daily rainfall for (A) RIB and (B) GRA basins for the years 1996–1998.

(Fontes et al., in press). Difficulties in relating soil suction measured in the laboratory to the water regime of allophane soils in the field were observed by Maeda et al. (1977). Because the underestimation periods correspond to dry spells when runoff does not occur, the effects of underestimating the low soil water storage are minimal when using the model

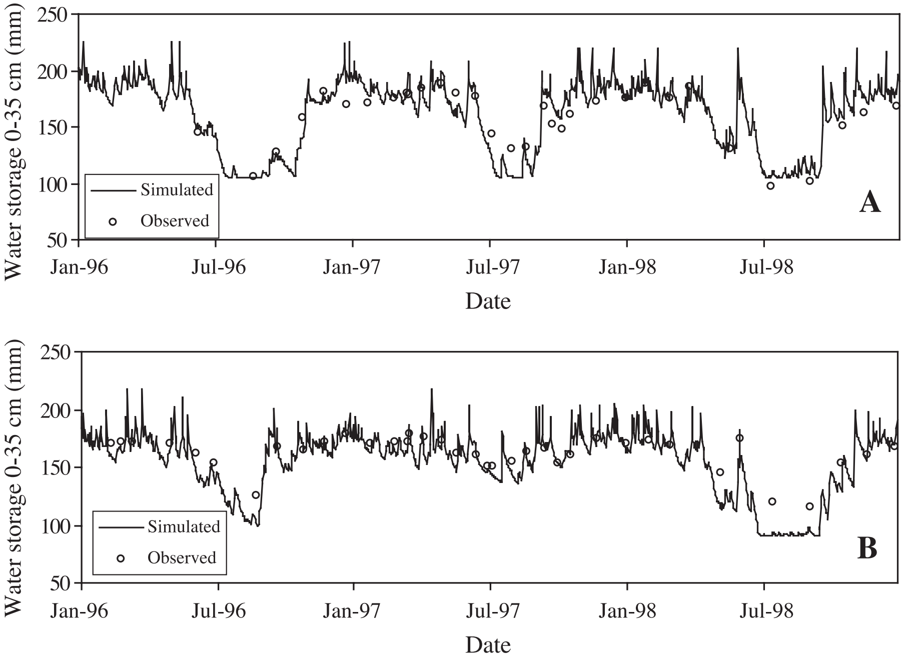

Fig. 5. Simulated and observed soil water storage for (A) RIB and (B) GRA basins for the years 1996–1998 (simulations using breakthrough rainfall data).

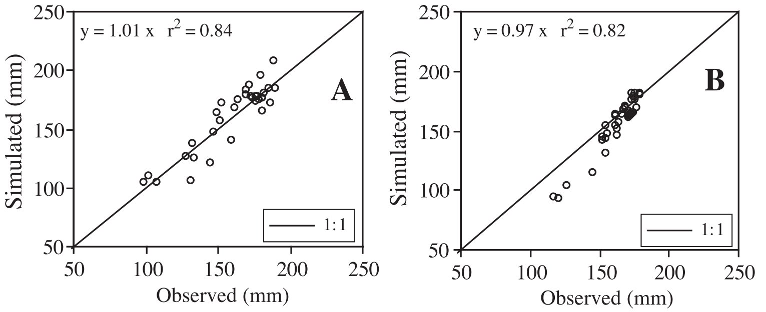

Fig. 6. Comparison of observed and simulated soil water storage at (A) RIB and (B) GRA basins.

to simulate runoff. Nevertheless, the results indicate the ability of the model to predict soil water storage using breakthrough daily rainfall data provided that the soil water characteristics are well defined.

When using daily rainfall data, the simulated and observed values of soil water storage to 35 cm depth are similar to those obtained using breakthrough rainfall data. The regression coefficients (b) are 1.02 and 0.97 for the basins RIB and GRA, respectively, and the r^2 values are 0.82 and 0.83, not significantly different from those given above for the simulations using breakthrough rainfall data. The results therefore show that OPUS has the ability to simulate the soil hydrologic processes of Azores soils.

4.2. Runoff and erosion

Only a few small runoff events, totaling $<1\%$ of rainfall, were observed in the grasslands. Greater runoff occurred only in one exceptional event, but unfortunately, it could not be measured because the equipment was damaged by the storm runoff. The runoff process is non-hortonian because of the high infiltration rates (Table 1), which are favored by the vegetation cover. Most storm water infiltrates, so that, except for very large storms, only the lower areas, where the soil becomes saturated, yield a small subsurface stormflow. Late in the storm, the saturated areas increase upslope and subsurface flow may ex-filtrate creating runoff. Areas producing stormflow vary inside the basin, partly because of the effect of compaction by grazing livestock. This type of hydrologic behavior on sloping areas with high infiltration soils and good vegetation cover is well known (e.g. Dunne and Leopold, 1978).

The model computes runoff following a typical hortonian approach since runoff is considered to occur when rainfall exceeds infiltration. However, as analyzed above for pasture cover conditions, a non-hortonian process occurs. Therefore, because the model is not able to simulate areas yielding variable stormflow, the simulated and observed runoff hydrographs do not match whichever runoff modeling approach is used. On the contrary, for conditions where the soil was less protected by vegetation and infiltration was reduced, model simulations and observed data are in agreement (Fig. 7).

The summed runoff volumes observed and simulated for both watersheds using breakthrough rainfall data are presented in Table 3. Data for full grass cover conditions

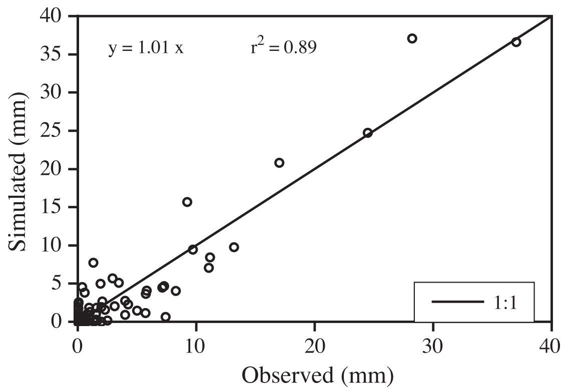

Fig. 7. Comparison of simulated and observed runoff water depths for the period of establishment of a new pasture in basin GRA (simulations using breakthrough rainfall data).

show that runoff barely exceeds 0.9% of the rainfall in GRA and 0.6% in RIB, so that most of the rainfall infiltrates. Runoff is greater in GRA than in RIB despite its smaller slope (8.9% vs. 16.4%), because the infiltration rate is higher in RIB (Fig. 1). These results support the suggestion that under grass stormflow mainly results from variable areas producing subsurface flow. This is also supported by the change in behavior observed for the period when a new grass cover was being established and the soil was unprotected or the vegetation cover was incomplete (Table 3). The steady-state infiltration in the soil surface layer, approximated by the saturated hydraulic conductivity, then decreased from 19.1 to 2.6 mm h^{-1}. The runoff process was then near hortonian and the model was able to reproduce runoff observations.

For the runoff events occurring during this period of new pasture development, the model predictions for simulated runoff volumes agree well with those observed (Fig. 7). For a regression through the origin in Fig. 7, the resulting regression coefficient (b) is 1.01 and the correlation coefficient (r^2) is 0.89. When daily rainfall is used, the regression parameters are similar, 0.98 and 0.88, respectively. However, for runoff depths < 8 mm, the correlation is weaker, suggesting that for these events, the runoff process is not fully hortonian, and stormflow may also be produced by variable contributing areas, as in

Table 3
Rainfall and runoff (mm) observed and simulated with OPUS for the experimental basins RIB and GRA for selected land uses and time periods

Land use	RIB			GRA			
	Pasture	Pasture	Pasture	Pasture	Maize	Pasture Installation	New Pasture
Observation period	Year 96	Year 97	Year 98	Year 96	April– September 97	October 97– May 98	June 98– December 98
Total rainfall (mm)	2075	1882	1405	2313	567	1402	821
Observed runoff (mm)	8.5	12.1	1.7	21.3	0	237.4	10.1
Simulated runoff (mm)	4.0	8.2	9.3	10.5	0	238.0	10.6
Runoff (% rainfall)	0.41	0.64	0.12	0.92	0	16.90	1.2

grasslands. In fact most of these events occurred under a partial vegetation cover, when infiltration was already recovering, rather than on bare soil.

No well-defined relationship between rainfall depth or rainfall intensity and runoff depth was observed, either for the periods when land use was grass or when the vegetation cover was partial. A relationship would be expected if hortonian overland flow occurs but not when variable areas contribute to stormflow through subsurface flow. This also supports the suggestions made above about the runoff processes.

The impact of land use on runoff yield is clearly indicated in Table 3. Runoff increased from < 1% of rainfall under pasture cover to nearly 17% when the vegetation cover was removed. This value would increase to >20% if the extreme event mentioned previously were included, as this corresponded to a simulated runoff equal to 93.2 mm when rainfall was 211 mm. As soon as pasture was established, the high soil infiltration rate recovered and runoff decreased to volumes similar to those observed before the grass cover was removed (1.2% of the rainfall). When the land use was silage maize, there was no runoff because rainfall was small (Fig. 4) and soil water contents were never very large (Fig. 5).

When overland flow was not produced or was near 1% of rainfall, as under pasture, erosion and sediment yield were very small (Table 4). As with runoff, the model was not able to reproduce the events when erosion occurred. In fact, the simulation procedures used in the model for both breakthrough and rainfall data relate sediment yield to runoff. Under these circumstances, the model does not have the sensitivity to simulate at the event scale the very small amounts of sediment observed. However, as with runoff, when the sediment produced is summed over a crop season or the whole year, the model results agree well with observations (Table 4). Table 4 shows that computations using either breakthrough or rainfall data produce similar results, close to the observations.

Table 4 shows that erosion and sediment yield are very small under dense pasture but increase greatly when the soil is unprotected or only partially covered by vegetation. The increase from < 5 kg ha^{-1} $year^{-1}$ to almost 15 ton ha^{-1} for the 8-month period of pasture establishment is explained by the changes in runoff (Table 3). It also reflects the characteristics of allophane soils, namely their high plasticity and weak aggregate stability

Table 4
Simulated and observed sediment production (kg ha^{-1}) in basins RIB and GRA for different land uses and time periods

Land use	RIB		GRA		
	Pasture	Pasture	Maize	Pasture installation	New pasture
Time period	Year 97	Year 98	April to September 97	October 97 to May 98	June to December 98
Observed (kg ha^{-1})	3.9	2.4	0	14 777	2.5
Simulated with breakthrough rainfall data (kg ha^{-1})	3.0	3.3	0	14 598	3.2
Simulated with daily rainfall data (kg ha^{-1})	4.4	1.3	0	14 564	1.5

when the soil is wet (Parfitt, 1990). Rapid erosion may also be attributed to the low clay content and to organic matter mineralization during and immediately after cultivation.

Our results suggest that establishing pasture would be better in the spring than during the fall–winter period, when rain storms are more frequent and intense. This would help to limit soil losses in periods when the soil is disturbed and less protected by vegetation.

5. Conclusions

The use of the model OPUS to simulate the effect of land use on soil water storage, runoff and sediment production by erosion in the volcanic islands of Azores was successful when the model was appropriately calibrated. Model parameterization was important especially in relation to soil hydraulic properties. Accurate water retention, hydraulic conductivity and infiltration measurements played a major role in the successful prediction of hydrologic processes in the Andosols of Terceira under different land uses. However, the capabilities of the model to simulate runoff were hampered by non-hortonian runoff processes, with variable areas contributing to stormflow because the model simulates runoff only as infiltration excess. When summed over long periods, such as a crop season or full year, runoff volumes and soil losses simulated by the model matched observed data very well.

Observed and simulated results show that under pasture, runoff is $<1\%$ of total rainfall but increases sharply to near 20% of the rainfall when the soil is tilled and not protected by vegetation. The sediment produced by erosion corresponded to <5 kg ha^{-1} year^{-1} under pasture cover, but increased to almost 15 ton ha^{-1} during the period when the soil was disturbed by tillage and less protected by vegetation. The OPUS model, when appropriately calibrated, can be used to simulate the impacts of land use on hydrologic processes when the spatial scale is similar to that of the model.

Acknowledgements

This research is funded by FCT (Portuguese National Foundation for Science and Technology) through a Research Contract PRAXIS-EMG relating to the study of global change impacts on land use in the Azores.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrig. Drain. Pap., vol. 56. FAO, Rome.

Bennett, J.P., 1974. Concepts of mathematical modeling of sediment yield. Water Resources Research 10, 485–492.

Brooks, R.H., Corey, A.T., 1964. Hydraulic properties of porous media. Hydrology Paper, vol. 3. Colorado State University, Fort Collins.

Cameira, M.R., Ahuja, L., Fernando, R.M., Pereira, L.S., 2000. Evaluating field measured soil properties in water transport simulations using the RZWQM. Journal of Hydrology 236, 78–90.

Diekkrueger, B., Smith, R.E., Krug, D., Baumann, R., 1991. Validation of model system OPUS. In: Bork, H.R., de Ploey, J., Schick, A.P. (Eds.), Erosion, Transport and Sedimentation Processes. Theories and models. Catena Suplement, vol. 19. Catena Verlag, Cremlingen, pp. 139–153.

Dunne, T., Leopold, L.B., 1978. Water in Environmental Planning. W.H. Freeman and Company, San Francisco.

Fontes, J.C., Gonçalves, M.C., Pereira, LS., 2004. Andosols of Terceira, Azores: measurement and characterisation of soil hydraulic properties. Catena. 56, 145–154.

Foster, G.R., 1982. Modeling the soil erosion process. In: Haan, C.T, Johnson, H.P., Bakensiek, D.L. (Eds.), Hydrologic Modeling of Small Watersheds. ASAE Monograph, vol. 5. American Society of Agricultural Engineers, St. Joseph, MI, pp. 297–382.

Jensen, M.E., Burman, R.D., Allen, R.G. (Eds.), 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manual, vol. 70. American Society of Civil Engineers, New York.

Knisel, W., 1980. CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. USDA Conservation Research Report No. 26.

Maeda, T., Takenaka, H., Warkentin, B.P., 1977. Physical properties of allophane soils. Advances in Agronomy 29, 229–264.

Morel-Seytoux, H.J., Verdin, J.P., 1983. Correspondence between the SCS CN and infiltration parameters (Ks, Sf). Proceedings of ASCE Specialty Conference on Advances in Irrigation and Drainage: Surviving External Pressures. ASCE, New York, pp. 308–319.

Musy, A., Pereira, L.S., Fritsch, M. (Eds.), 1999. Emerging Technologies for Sustainable Land Use and Water Management. Presses Polytechniques et Universitaires Romandes, Lausanne (CD_ROM).

Parfitt, R.L., 1990. Allophane in New Zealand–a review. Australian Journal of Soil Research 28, 343–360.

Rawls, W.J., Goldman, G.L., Van Mullen, J.A., Ward, T.J., 1996. Infiltration. In: Heggen, R.J. (Ed.), Hydrology Handbook, 2nd ed. ASCE Manual, vol. 28. ASCE, New York, pp. 75–124.

Ritchie, J.T., 1972. A model for predicting evaporation from a row crop with incomplete cover. Water Resources Research 8, 1204–1213.

Saint-Venant, A.J.C.B., 1871. Théorie du mouvement non permanent des eaux avec application aux crues des rivières et à l'introduction des marées dans leur lits. Comptes Rendus des Séances de l'Académie des Sciences (Paris), 73, 147-154 and 237–240.

Sharpley, A.N., and Williams, J.R., (Eds), 1990. EPIC: Erosion/Productivity Impact Calculator: 1. Model Documentation. U.S. Department of Agriculture Technical Bulletin No. 1768.

Smith, R.E., 1992. Opus: An Integrated Simulation Model for Transport of Nonpoint-Source Pollutants at the Field Scale, Vol. I. Documentation. U.S.D.A. Agr. Res. Serv., ARS-98.

Smith, R.E., 1995. Simulation of crop water balance with Opus. In: Pereira, L.S., van den Broek, B.J., Kabat, P., Allen, R.G. (Eds.), Crop-Water-Simulation Models in Practice. Wageningen Pers, Wageningen, pp. 215–227.

Smith, R.E., Parlange, J.Y., 1978. A parameter-efficient hydrologic infiltration model. Water Resources Research 14, 533–538.

Soil Conservation Service, 1972. Estimation of direct runoff from storm rainfall, National Engineering Handbook, Chapter 10. Soil Conservation Service, US Gov. Print. Office, Washington, D.C.

Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modeling approach to determining the relationship between erosion and soil productivity. Transactions of the ASAE 27, 129–144.

Williams, J.R., Jones, C.A., Dyke, P.T., 1990. The EPIC model. In: Sharpley, A.N., Williams, J.R. (Eds.), EPIC: Erosion/Productivity Impact Calculator: 1. Model Documentation. USDA Technical Bulletin, vol. 1768. USDA, pp. 3–92.